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A parametric model for barred equilibrium beach profiles

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ABSTRACT

Environment predictions for locations for which bathymetric data is missing, poor or outdated requires the use of some sort of representative bathymetric form, usually one that is concave up but monotonic. We propose and test a parametric form that superimposes realistic sand bars (Ruessink et al., 2003b) on a background profile that mixes a concave up nearshore with a planar far field behavior. Implementation at any new site involves estimation of five parameters, three that can be found from approximate information from climatology or old offshore charts, one that can be estimated by almost any remote sensing modality and one, h_{sea} that is less well understood but mostly affects deeper bathymetry that has little impact on the resulting surf zone hydrodynamics. Tests against several hundred surveys at three diverse locations show that bathymetry is better estimated by the new barred form than with a previous monotonic profiles in about 80% of cases. The remaining cases are usually associated with the parametric prediction of bars that look realistic but are out of phase. The presence of parametric bars has an even greater impact on predicted hydrodynamics since wave breaking is concentrated at sand bar locations. Modeled cross-shore transects of alongshore current and wave height over the measured survey profile are well represented by modeled transects over the barred parametric form but not for results over a Dean profile. The peak alongshore current strength and location are particularly sensitive to the presence of a sand bar.

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1. Introduction

A primary goal of research in the nearshore zone (defined here as the region where waves are significantly affected by the bottom) is to predict the hydrodynamics and morphodynamics driven by waves propagating over sandy beaches. Response depends strongly on the pre-existing bathymetry, a variable that can be measured only with great effort and that changes rapidly on time scales that range from days to weeks under wave and storm forcing, to decades and centuries under changing climate and sea level. Given the impracticality of measuring or predicting these changes over time, there is a clear need to develop parametric forms for bathymetry that approximate the important features of beach form as it affects hydrodynamics. The most common class of assumed parametric forms is equilibrium beach profiles (EBP), technically the asymptotic shape approached by a beach profile under constant forcing, but other climatologically-representative forms could also be used as long as they represent typical (preferred) forms under natural forcing.

Equilibrium beach profile forms have been studied extensively as a most plausible proxy for cases of unknown or poorly known bathymetry and also for long-term applications such as beach response to sea level rise (see Özkan-Haller and Brundidge (2007) for a recent review). Ideally, the shape of an EBP is found from an assumed depth-dependent sediment transport equation by finding the profile shape for which the transport is equal to zero everywhere, for example as done by Bowen (1980). However, they are more commonly just simple parametric forms with desirable characteristics such as being concave upward.

The best known EBP form is the power law approach first proposed by Bruun (1954) but commonly referred to as the Dean profile due to his extensive field investigations into the problem (e.g. Dean, 1991)

$$h = Ax^{2/3} \tag{1}$$

Here h is depth, x is cross-shore distance from the shoreline and A is a dimensional constant that was found to depend on an assumed uniform sediment grain size (see, for example, Dean, 1987). This form was empirical but motivated by the concept that transport should redistribute sediment such that the breaking dissipation per unit volume will be constant. This model has the advantage of simplicity, has only one parameter that can be determined, in principle, from local site information, and represents the expected concave-up form typically found on wave-dominated beaches. However, the slope at the shoreline is infinite, a problem in some calculations, and decreases continually offshore making it hard to match the typical planar continental shelf outside the nearshore wave zone. Thus the model is typically applied only over a limited cross-shore span.

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Several alternate forms have been proposed to deal with the shoreline singularity. Larson and Kraus (1989) suggested a form that superimposed a planar shallow water component with an offshore Dean form. Özkan-Haller and Brundidge (2007) suggested a modification to further limit the influence of the planar component to shallow water. Bodge (1992) and Komar and McDougal (1994) suggested an exponential form as a preferred solution that exhibited finite slope at the shoreline and a desired concave up profile. However, profiles unrealistically flattened to a horizontal surface offshore.

The solutions discussed above capture desirable characteristics for long-term average profile shape so they can be useful for investigations of long-term sediment volume response, for example, to rising sea level. However, they cannot represent the near-ubiquitous presence of sand bars. Since wave dissipation is focused over bars, hydrodynamic predictions such as nearshore circulation or peak wave height made using beach profiles that omit these features will have little value.

Ruessink et al. (2003b; hereafter RWHKvE03) investigated the possibility of representing barred profiles by analyzing extensive data sets from six beaches around the world and developing a general equation (described in the section below) that represented sand bars in terms of a sinusoidal function with spatially varying amplitude and wavelength. This bar function, h_{bar}, is superimposed on an underlying background bathymetry, h_0, that might be derived from long-term average data or from one of the EBP equations noted above. Thus the total bathymetry would be

$$h(x,t) = h_0(x) + h_{bar}(h_0, t) \tag{2}$$

where we have assumed only a cross-shore dependence (alongshore variability would be represented by implementing Eq. (2) in an alongshore variable way). Because the bar function is formulated in terms of depth, the selected h_0 must be a reasonable representation of the time-mean bathymetry at the site.

The purpose of this paper is two-fold. The first is to introduce a new EBP form that satisfies the requirements of a) finite shoreline slope, b) a concave up form in wave-dominated shallow waters, and c) an asymptotic planar slope in the far field. The second is to develop and test methods to apply the combined bathymetry model (Eq. (2), combining the new background EBP model with the barred model of RWHKvE03) at any site, where the main required input for any realization is a single bar location estimate such as can be determined from wave breaking patterns detected in remote sensing images.

The next section describes the new EBP model and the methods for superimposing the Ruessink model with minimal inputs. This is followed by a section testing the resulting bathymetry predictions using data from three natural beaches and a section comparing hydrodynamic predictions using parametric profiles with those from measured profiles. Thereafter follow discussion and conclusions.

2. EBP profile model

2.1. EBP background profile model

We require a parametric background profile that is concave near the shore but asymptotes to a planar form offshore, mimicking the transition from shapes that are associated with waves versus geological shelf processes. We propose a mix of a planar form with an exponential shoreward component,

$$h_0 = \alpha + \beta + \gamma \exp(-kx) \tag{3}$$

and refer to this as a composite profile. As for the Dean Eq. (1), we assume a shore-based coordinate system so h = 0 at x = 0 and Eq. (3) can be re-written

$$h_0 = \gamma[\exp(-kx) - 1] + \beta x. \tag{4}$$

Here β, γ and k are three unknown empirical coefficients. Thus, three boundary conditions are needed.

It will be assumed that the value for β, the asymptotic offshore beach slope, can be estimated independently from charts or other information to be β_0. Similarly, we will assume that depth, h′, is known at some location, x′ (which can be anywhere on the profile but should be representative of the background, average, profile depth so should best be a point seaward of the active sand bar zone). Thus,

$$hx' = \gamma\left[\exp\left(-kx'\right) - 1\right] + \beta_0 x'. \tag{5}$$

The third boundary equation could also be based on another known depth but it is likely that any shoreward point that could help constrain the exponential part of the profile will be influenced by temporally varying sand bars. Instead, the final boundary condition was solved by assuming that the shoreline beach slope was known or could be easily determined. Taking the derivative of Eq. (4) to find slope

$$\frac{dh_0}{dx} = -\gamma k \exp(-kx) + \beta_0. \tag{6}$$

If the shoreline slope is β_s, we have

$$\beta_s = -\gamma k + \beta_0. \tag{7}$$

Note that β_s must be an estimated climatological slope, not an instantaneous fluctuating value. Eqs. (5) and (7) can be solved simultaneously (numerically) to find k and γ. If the profile is convex up (β_0 intersects the shoreline above z = 0) the solution is imaginary and a plane slope is substituted from x′ to the shoreline.

Fig. 1 shows an example comparison between the Dean and composite background profiles along with an example bathymetry from Duck, NC, on September 16, 2009. The addition of the exponential term allows more profile curvature close to the shoreline and corrects a Dean profile problem of under-predicting shallow water depths. Since the bar profile, described below, depends on depth, this change is important to nearshore bar parameterization. Note that nearshore curvature can also be better estimated by using different exponents in

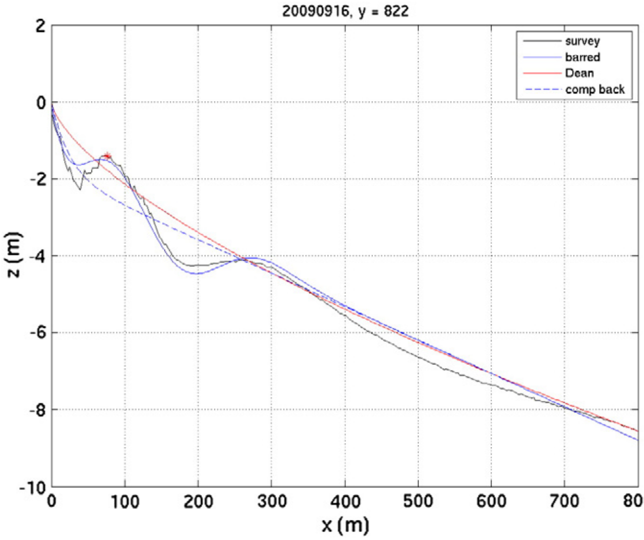

Fig. 1. Comparison of the Dean (red solid), the composite (blue dashed) background profile and the parametric barred profile (solid blue; discussed below) with an example CRAB survey transect (black solid) from Duck, NC, Sept 16, 2009 (y = 822 m). Neither background form is capable of representing the sand bars although the composite profile has a much lower bias, especially near the shore. The red asterisk indicates the automatically selected x_b for this profile, discussed below.